

Phase Control and Beam Steering of Semiconductor Laser Arrays

J. Katz

Communications Systems Research Section

The operational principles and a possible device configuration of one-dimensional monolithically integrated semiconductor laser arrays are described. The output beam of the array can be electronically steered. Devices of the type described in this report can find applications in optical communication systems where the power levels needed are above the capability of a single laser device.

I. Introduction

Among the most promising candidates for light emitters in optical communication systems are semiconductor injection lasers (Ref. 1). These lasers are far more reliable than other laser types. In addition, they are much more efficient, and possess the small size and ruggedness typical of semiconductor devices. These advantages are offset by the relatively low levels of power that can be emitted by them in a stable radiation pattern (typically a few milliwatts in CW operation and about an order of magnitude more in a low duty cycle operation). Although research efforts are currently being conducted in order to improve this limitation (Refs. 2-4), it is conceivable that some applications, such as communication links for deep space missions (Ref. 5), will still require more power than is available from a single device.

A possible solution to this problem is to combine, coherently (Refs. 6-9) or incoherently (Refs. 10-14), the power of several lasers. Coherent power combining, via phase locking of the lasers, has several advantages over noncoherent power combining. First, when the power of the lasers is combined incoherently, each laser emits light in its individual spectrum. Thus it is necessary to have an optical filter with a wider band-

width at the receiver, with the penalty of increased detected background noise radiation. Secondly, the locking of the lasers causes a reduction in the far-field beam divergence angle. This makes the task of subsequent beam narrowing simpler (e.g., by requiring an optical telescope with a smaller magnification). As will be described in a subsequent section, coherent power combining also makes monolithic beam steering of the laser array possible.

As pointed out in a recent report (Ref. 15), the requirement for maintaining phase locking among the lasers in the array is quite stringent. Roughly speaking, the intrinsic frequencies of oscillation of the individual lasers must be maintained within a very close proximity of each other, typically within a relative deviation of a few tens of ppm. Modifying the oscillation frequency by changing the amount of current flowing through the laser is possible but not desirable, since it is better to be able to independently control both the amplitude and the frequency of each laser. Section II of this report describes a method to achieve a moderate amount of frequency control by incorporating an intracavity electrooptic modulator into the laser cavity, thus mitigating the problem of achieving phase-lock condition among the lasers of the array.

In addition, some applications, which involve operations such as beam pointing and tracking, can benefit from the incorporation of electronic beam steering, in a similar fashion to the microwave phased arrays. Section III of this report describes two methods of implementation: one which utilizes a discrete beam deflector element external to the array (and thus can be used also with incoherent arrays or single lasers), and a second method which monolithically incorporates an individual phase-shifter in tandem with every laser in the array. By controlling the phase shift of each device, we can first bring the array to oscillate in the fundamental, well-behaved mode, and also deflect the radiation pattern by the desired amount.

Although several physical phenomena can be used to control light waves, the use of the linear electrooptic (EO) effect is considered here (Ref. 16). In the most basic form of the linear EO effect, the change in the index of refraction of the material is proportional to the electric field applied on it. (Because of the anisotropy of actual crystals, the relation is a tensorial, not a scalar one.) The reason for considering this particular effect is twofold. First, since it involves the application of voltages, the power consumption can be minimal (unless the voltage is applied on medium or low resistivity materials, or when dealing with high frequency operation). Secondly, since GaAs, which is the intended substrate material of the injection lasers used in our application is also a quite strong electrooptic material, monolithic integration of lasers and modulators is possible, as described below.

Whereas Sections II and III review the application of the internal and external phase shifters to the individual laser devices, Section IV briefly addresses the specific problems of implementing the phase control mechanisms in the densely packed array configurations.

II. Frequency Control of Semiconductor Lasers Using an Intracavity Electrooptic Modulator

Consider a laser cavity that is made of two sections, as shown in Fig. 1. The first section is a regular laser-amplifier section. The length of this section is ℓ_a , and the electromagnetic mode of the laser propagates in it with a propagation constant $\beta = kn_a$, where $k = 2\pi/\lambda$ and n_a is the effective index of refraction. In the second (modulator) section, of length ℓ_m , the effective index of refraction n_m , seen by the laser radiation mode, is a function of the applied electric field \mathcal{E} .

The phase condition for oscillations, which demands that the round-trip phase delay of the laser mode in the cavity

is an integer (p) multiple of 2π (Ref. 16, Ch. 9), can be written as:

$$\frac{\omega_p}{c} [\ell_a n_a + \ell_m n_m(\mathcal{E})] = p\pi \quad (1)$$

where ω_p is the (radian) frequency of the p th mode. Differentiating Eq. (1) with respect to n_m yields

$$\frac{\Delta\omega_p}{\omega_p} = - \frac{1}{1 + \frac{\ell_a n_a}{\ell_m n_m}} \frac{\Delta n_m}{n_m} \quad (2)$$

i.e., the relative change in the frequency is proportional to the relative change in the index of refraction in the modulator section.

The change of the index of refraction with the electric field is explained with the help of Fig. 2, which shows a GaAs crystal cleaved in the orientation used in fabricating semiconductor injection lasers. (x, y, z) and (x', y', z') are the principal coordinate systems for $\mathcal{E} = 0$ and $\mathcal{E} \neq 0$, respectively (Ref. 16). The mode of the semiconductor laser is predominantly TE polarized; i.e., the electric field of the optical wave is parallel to the y' axis. In this configuration the index of refraction seen by the laser field propagating in the modulator section is changed from n_m by an amount Δn_m given by (Ref. 16):

$$\Delta n_m = -\frac{1}{2} n_m^3 r \mathcal{E} \quad (3)$$

where r is the electrooptic tensor element relevant to this configuration. The largest field \mathcal{E}_m that can be applied is the one beyond which phenomena such as avalanche set in. For GaAs $\mathcal{E}_m \gtrsim 3 \cdot 10^5$ volts/cm (depending on the doping), $n_m \approx 3.6$ and $r \approx -1.5 \cdot 10^{-10}$ cm/V. Several assumptions are implied in the above analysis. It is assumed that the modulator section is a depletion region of a reverse biased pn junction. Furthermore, by properly designing the doping concentrations and the dimensions of the device, and utilizing heterojunctions, the electric field can be made to be uniform over the region occupied by the optical mode, and the optical mode itself will have its characteristics virtually unchanged when the voltage imposed on the device is varied. A possible design is depicted in Fig. 3.

Using the above numbers, we find that the maximum relative change in index of refraction that can be modified via the linear EO effect is

$$\frac{\Delta n_m}{n_m} \approx 3 \cdot 10^{-4} \quad (4)$$

As will be discussed later, the modulator section is fabricated of GaAlAs so that the light that is generated in the GaAs active region of the laser-amplifier section can propagate in it without being strongly absorbed. Although the various parameters in Eq. (3) are different in GaAlAs and GaAs, the results of Eq. (4) still approximately hold.

Using Eq. (4) in Eq. (2), it is seen that the laser frequency can be modified by a fractional change of about 10^{-4} . Since $\Delta\omega/\omega = \Delta\lambda/\lambda$, this means changing the wavelength by up to about 1 Å ($\lambda \cong 0.8 - 0.9 \mu\text{m}$).

Such a device — which combines on the same substrate the operation of an injection laser and the intracavity modulator — has been demonstrated (Ref. 17). The voltage was applied to the modulator section in the configuration of a reverse biased junction, and wavelength modulation of up to 0.4 Å was obtained. Using a different device configuration, still better performance may be achieved, in particular with respect to the threshold current density and amount of frequency modulation. This subject will be further discussed in the next section.

III. External Phase Control of Semiconductor Lasers Using Electrooptical Modulators

The electrooptic effect which was described in the last section, can also be utilized for controlling the phase of the light wave emitted from the laser. The first application is the deflection of the radiation pattern (Ref. 16). By placing a prism which is made of an electrooptical material (e.g., KDP) in the path of the light beam (which can come from either a single laser or an array), as shown in Fig. 4, the beam is deflected by an amount $\Delta\theta$ equal to

$$\Delta\theta = \frac{\ell}{D} n^3 r \mathcal{E} \quad (5)$$

where ℓ is the length of the prism, D is its width and n is its index of refraction. The dynamic range of the beam deflection, measured in beamwidths, is proportional to ℓ . A typical value is 1 beamwidth for a 1-cm-long prism.

The second possible application of the electrooptic effect is the fabrication of an electrooptic modulator on the same substrate with the laser, but external to the laser cavity. A cross section of a possible device is shown in Fig. 5. The amount of additional phase shift $\Delta\phi$ introduced to the laser radiation field is approximately given by

$$\Delta\phi = \frac{2\pi}{\lambda} \ell_x \frac{1}{2} n_m^3 r \frac{V}{d} \quad (6)$$

where d is the thickness of the region on which the voltage V is applied, and ℓ_x is the length of the external phase shifter (see Fig. 5). From Eq. (6) it is seen that the amount of phase shift is proportional to ℓ_x . Typical values that can be obtained are 1 radian for $\ell_x = 100 \mu\text{m}$.

Of course, applying a phase shift to a single laser is of no significance to our application. However, if we have a phase-locked array of semiconductor lasers, then by individually controlling the relative phase shifts among the various lasers, we can obtain a controlled beam deflection of the entire array, in a similar fashion to microwave phased arrays. Operation of a semiconductor laser device on similar principles has been recently demonstrated (Ref. 18). We should also note that the dynamic range of the beam steering in this case is contained within the far-field radiation pattern of the individual lasers of the array.

IV. One-Dimensional Beam Steerable Semiconductor Laser Array

A typical application (e.g., source for an optical communication system) may call for the use of both types of electrooptic modulators: intracavity modulators (described in Section II), which fine-tune the oscillation frequency of the individual lasers in the array, thus making the phase locking possible, and external modulators (described in Section III), which electronically control the beam shape and deflection of the array.

Both modulators can be fabricated in the same processing procedure. It is worth noting that just by applying antireflection coating to different facets in the device, the modulator section shown in Fig. 5 can operate both inside and outside the laser cavity, thus performing both functions. Of course, other device configurations are also possible.

When operating as elements of an array, the individual devices are placed in close proximity to each other, typically about $10 \mu\text{m}$ or less. Since the electrical contact of the total device must be in the size of at least $50 \times 50 \mu\text{m}^2$, a two-level metallization is needed for the contacts (as opposed to the one-level metallization used for single devices). Also the metal stripes that connect the devices themselves (especially the lasers) and the external contacts should not have high resistivity.

An example of a one-dimensional beam steerable semiconductor laser array is shown in Fig. 6. The figure shows a schematic configuration of one-half of a four-element array. Several technical details are omitted (as described in the figure caption), but the main ingredients of the device —

the laser section, the modulator — are clearly depicted. Extension of such arrays to more than four elements is straightforward. The functions of the various parts of each element of the array have been described in the previous sections, and the mechanism by which all the individual components operate in a coherent fashion was analyzed in Ref. 15.

V. Conclusions

The operational principles and a possible device configuration of one-dimensional monolithically integrated semiconductor laser arrays have been described. Two electro-optic modulators accompany each laser-amplifier element of the array. One of the modulators is placed inside the laser cavity, making

fine-tuning of the laser frequency possible, thus alleviating the problem of maintaining phase-lock conditions across the array. The second modulator, which is external to the laser cavity, controls the phase of the optical wave emitted by the laser. By judiciously controlling the phases of all the elements, controlled beam steering capability of the array is expected.

Arrays of the types described in this report may be useful in applications which call for a single and stable mode operation of semiconductor light sources in applications where the amount of power needed is beyond the capability of a single injection laser device. Among the possible applications are deep-space, intersatellite and near-earth optical communication systems, and optical radars.

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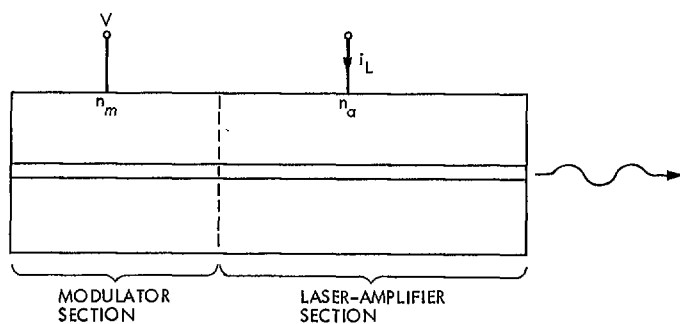


Fig. 1. Schematic cross section of a semiconductor laser with an intracavity modulator. n_a and n_m are the indices of refraction of the representative sections.

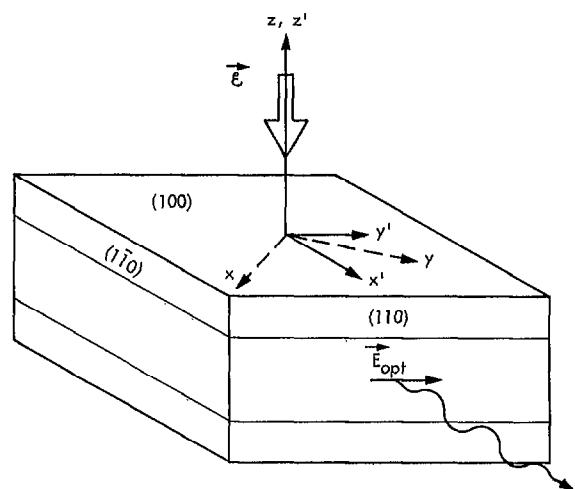
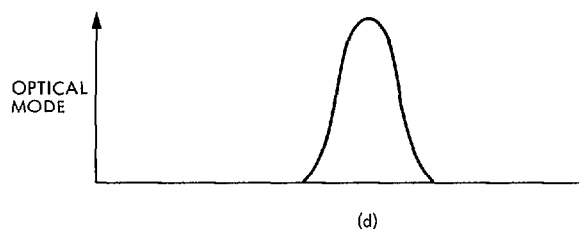
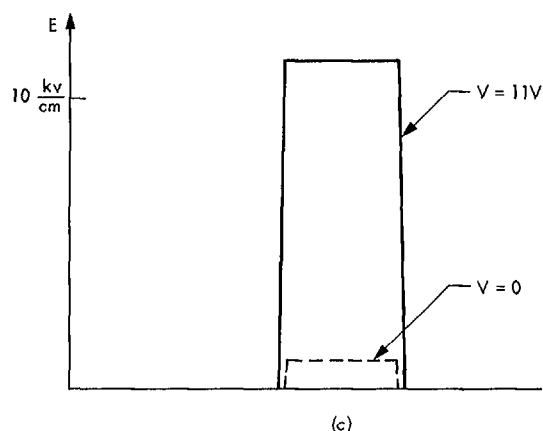
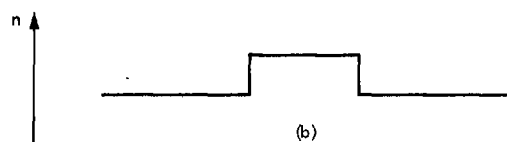
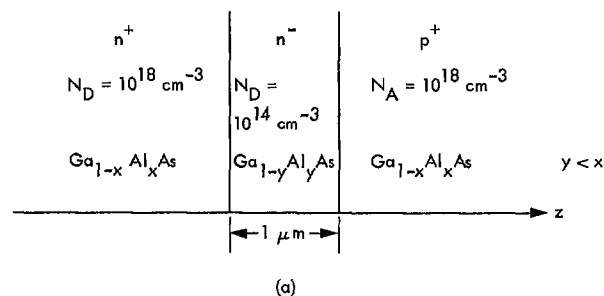


Fig. 2. GaAs electrooptic modulator. The GaAs crystal is cut in the same orientation used for fabrication of semiconductor lasers. (See text for details of coordinate systems.) \vec{E} is the electric modulation field and \vec{E}_{opt} is the electric TE field of the optical wave.

Fig. 3. Design example of an electrooptic modulator in a reverse biased pn junction configuration. a) Electrical structure. b) Index of refraction (almost unchanged by the applied field). c) Electric field distribution for various applied voltages. d) Intensity profile of the optical mode

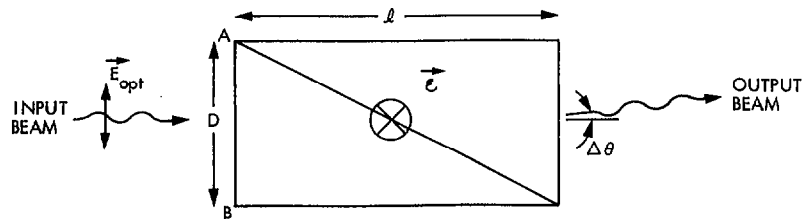


Fig. 4. Double-prism electrooptic beam deflector. \mathcal{E} is the applied electric field (Ref. 16). The optical path for waves entering the input plane (AB) at different points vary, thus causing a tilting of the wavefront by $\Delta\theta$

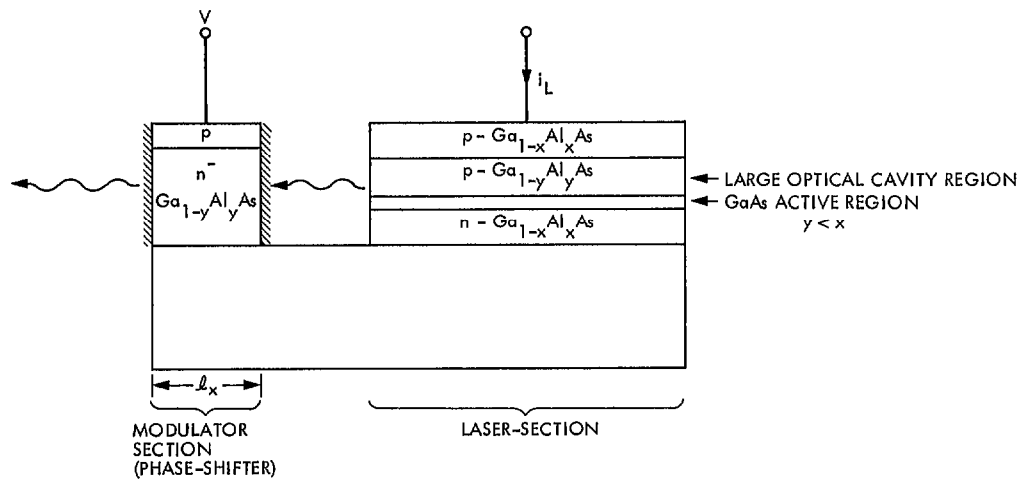


Fig. 5. Cross section of a possible monolithic implementation of a semiconductor laser and an external electrooptic phase-shifter. (The cross-hatched facets depict layers of antireflection coating to prevent coupling from the phase-shifter back to the laser.)

